# BIOFOULING CONSIDERATIONS IN THE DEVELOPMENT OF ATLANTIC CANADA'S OFFSHORE PETROLEUM INDUSTRY

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This work has been prepared for the Canada Centre for Mineral and Energy Technology, Energy Mines and Resources Canada. The information represented and the opinions are not the responsibility of the department.

DSS File No. 155Q 23440-4-9241
DSS Contract Serial No. 1SQ84-00258

March, 1985.

OCT 3 0 1985

72 pp.

MICROMEDIA

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ABSTRACT

An exhaustive study was undertaken to assemble and analyze available information on the nature and impacts of marine macrofouling, microfouling, and biocorrosion on Atlantic Canada's offshore hydrocarbon exploitation industry.

Information was obtained from public and private sources in Canada and abroad.

The analysis of the data indicates that Canadian government and industry efforts in this regard fall far short of the needs. By comparison, programs in place in the North Sea petroleum industry include ongoing monitoring and predictions of potential impacts to be expected from fouling communities on offshore structures.

Through industry/government/university and private research efforts, considerable data have been developed which form the basis for decision-making on the part of industry in designing and maintaining structures and equipment in the North Sea.

It is concluded that for the safe and successful exploitation of Atlantic Canada's offshore petroleum resources, a similar program will have to be developed. Further, because of the differences in physical and biological characteristics of the North Sea and the Northwest Atlantic, data and experiences from the former are not directly applicable to the latter.

Recommendations are provided concerning the development of a distinctly Canadian program to service this important attribute of offshore petroleum development.

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## 1.0 INTRODUCTION

The development of Canada's offshore petroleum industry depends upon first locating, and subsequently bringing ashore the oil and gas from continental shelf reserves. Both operations involve the use of large marine structures, moored in some fashion, at a distance from a few to more than 100 miles from land. In the first case, mobile exploration rigs, capable of being moved from one site to another, are used to gain access to the deposits; and in the second, permanent production platforms are subsequently placed over the well head and the oil/gas pumped into tankers or piped across the sea bottom to onshore facilities.

Because both exploration and production platforms are exposed to the marine environment, their design and construction must make provision for all the adverse conditions imposed by the sea.

At a glance, biological fouling communities, which inevitably develop on such stationary structures, appear relatively innocuous. However, in fact this is not so, since recent experience in other parts of the world has given strong indication that biofouling and the associated process of biocorrosion play a significant role in affecting the performance of offshore rigs. The potential for the greatest impact rests with fouling of the production platforms whose useful life may be spent entirely at sea.

Biofouling/biocorrosion are insidious problems, since their effects on a rig are manifested only after a prolonged period at sea, during which time the fouling process gradually develops. Consequently, there is a tendency for operators to minimize its importance, when compared with more dramatic concerns such as severe storms or threats of collision with icebergs.

Biofouling/biocorrosion are industry-wide problems which have not, as yet, been addressed in a comprehensive manner in Canada. The problems experienced in areas such as the Gulf of Mexico and the North Sea leave no doubt that this is a facet of industry development which

requires considerable attention in Canada. For example, in the North Sea fatigue of rig components has been linked to severe corrosion occurring beneath fouling communities. In a few cases the added weight contributed by the fouling community has been shown to be as much as 10 times that predicted for platform fouling, resulting in increased hydrodynamic loading.

Currently, Canada is lacking data related to specific fouling problems of mobile and permanent platforms and of the materials (steel, concrete) used in their construction.

## 1.1 Objectives

The broad objective of this study was to provide industry and government with an up-to-date review of the importance of biofouling and biocorrosion in the development of the Canadian offshore petroleum industry.

This broad objective will be considered in terms of the following immediate objectives:

i) Assemble and analyze existing biofouling/biocorrosion data related to hydrocarbon production off Canada's Atlantic coast.

ii) Assemble and analyze data from the North Sea and other areas of the world with similar conditions, and comment on its relevance to the Canadian Atlantic situation.

iii) To recommend areas for further study.

## 2.0 DESCRIPTION OF THE FOULING PROCESS
(A Chronological Summary of the General Course of Fouling)

### Introduction

Biofouling refers to the cumulative growth of plants, animals, and microbial organisms on immersed or partially immersed surfaces (Gaythwaite, 1981). Marine fouling organisms have a tendency to move upwards and outwards occupying the maximum area of nutrient and energy rich water (Anon.[1], 1980).

Fouling communities may be divided into two major groups: Macrofouling - which includes all visible plant and animal foulants in the marine environment, and Microfouling - the microorganisms present within the fouling community. The initial phase in the fouling process is the establishment of a microfouling community or "slime layer," which is then and only then followed by the settlement and development of macroorganisms (Oldfield, 1980; Kirchman and Mitchell, 1983; Colwell, 1984; Lihach, 1984).

### 2.1 Chemical Adsorption

While the macrofouling colonization of an offshore structure varies in relation to geographic position and time of year, the initial fouling sequence tends to follow a set pattern (Terry and Edyvean, 1984; Berk et al, 1981; Dempsey[2], 1981). Dissolved organic material, initially adsorbed on to surfaces (primary film), is an important factor in providing nutrients and encouraging the initial settlement of bacteria and other micro-organisms (biofouling or microbial film). This adsorbed layer of biopolymer has a lower surface tension than the metal surface and thus increases the adhesion of organisms. Bacteria usually settle after only a few hours of immersion, and quickly form dense colonies producing copious mucilage. Diatoms are the first microalgae to settle on the substratum and are numerically second in importance to bacteria. These are closely followed by blue-green algae, protozoa, and zoospores of macroalgae (Thomas and Allsopp, 1983; Kirchman and Mitchell, 1983). This micro-

fouling assemblage makes up the "slime film" widely reported on submerged structures. The copious mucilage produced by the bacteria and algae of this film attracts large amounts of detritus and its inherent adhesive nature may encourage the settlement of other organisms, including invertebrate larvae. Generally, the older the microbial layer, the greater the polymer accumulation and the greater the number of invertebrate larvae associated with it (Kirchman and Mitchell, 1981).

## 2.2 Formation of Bacterial Slime

The process of microfouling film formation has been categorized into four stages (Corpe, 1979; Table 1). The first stage consists of chemical conditioning of the substrate (Dempsey[1], 1981; Corpe, 1979; Mitchell and Benson, 1981). "Molecular fouling" occurs spontaneously and instantaneously and consists of the adsorption of non-living material onto the solid surface. It is suggested that this material is comprised of organic polymers resulting from the breakdown of natural matter. This layer can build in thickness to over 500 Å in 10 hours (Loeb and Neihog, 1977).

In the second stage, free-swimming bacteria begin to colonize, but do not attach themselves firmly at first (reversible attachment), perhaps allowing further surface modifications to occur.

TABLE 1

STAGES IN THE DEVELOPMENT OF A MICROFOULING FILM
ON SOLID SURFACES IMMERSED IN NATURAL SEAWATER

| Stage | Descriptive Features |
|---|---|
| 1. Chemical conditioning | Rapid, perhaps instantaneous adsorption of large molecular weight substances from water; also perhaps concentration of low molecular weight substances as well. |
| 2. Attachment and colonization by bacteria | |
| a) pioneer bacteria | Mostly motile rod-shaped bacteria that attach irreversibly within a few hours and produce expolymers which aid attachment and construction of contiguous film. |
| b) other bacteria | Stalked, budding, and filamentous bacteria become most abundant and replace pioneer forms. |
| 3. Colonization by other microorganisms | Microalgae, attached protozoa, grazing protozoa; numbers and kinds vary with water source and conditions. Density and thickness increase with time. |
| 4. Accumulative | Adhesion of debris, detritus, inorganic particles may begin early but depends on preceding biological activity and character of suspended material. |

These bacteria exhibit a range of attachment mechanisms. Initial spontaneous attachment is mediated by simple stickiness of cell walls, flagella, pili (fimbriae) or stalks. This stickiness can be attributed to an actual adhesive, electrostatic forces, cell-surface plasticity, hydrophobic zones, electrical double layer phenomena, or to London/van der Wall forces (Carson and Allsopp, 1983; Dempsey[1], 1981; Mitchell and Benson, 1981). Properties of the solid surface (surface wettability, charge, and chemical composition) and the organic content and cation concentration (monovalent and divalent) of the surrounding water all influence this attachment (Gordon et al, 1981; Zaida et al, 1984; Dexter et al, 1975, Berk et al, 1981).

In the third stage these pioneer bacteria secrete insoluble, high molecular weight polymers (protein and carbohydrate) which act to bridge the space between the cell wall and substrate or adjacent cells. Continuing growth of adjacent colonies leads to the development of confluent films over the substrate surface.. Eventually the entire surface is coated with a dense community of mixed bacteria and their adhesive mucilage (Berk et al, 1981; Corpe, 1979; Dempsey[1], 1981). The secretion of this acidic extracellular plaque results in irreversible attachment, binding the cell firmly to the surface. Other bacteria, microalgae, (diatoms and unicellular green algae), protozoa (ciliates), fungi, and nematodes are attracted to the higher nutrient concentrations of the film and eventually replace the pioneer bacteria.

The method of attachment varies amongst diatom groups. Sessile marine diatoms may attach by substances secreted through the raphe, adhesive pads, mucilage capsules, mucilage sheaths, and/or stalks (Blunn and Evans, 1981; Terry and Edyvean, 1981).

Finally, the character of the microfilm may be further modified with the inclusion of particulate and detrital material, cell fragments, and debris, iron-utilizing bacteria and corrosion products and/or macroalgal zoospores and germlings (Thomas and Allsopp, 1983; Hudon and Bourget, 1981).

Two stages can be identified in the development of bacterial fouling communities (Dempsey[1], 1981). Initially, gram-negative rods such as the pseudomonads (principally species of Pseudomonas, Flavobacterium, and Achromobacter) are abundant. Gram-positive species never account for more than 10 to 15 percent of the population. The secondary colonizers (periphytes) are more exotic forms and can be identified within 24 to 72 hours of substrate immersion. They are usually stalked, budding, or filamentous species of Caulobacter, Hyphomicrobium, and Saprospira.

Rate limiting steps in biofilm development are the attachment of the conditioning film and primary microbial film. The secondary film can generally attach and regrow very rapidly, often within two to five days (Mitchell and Benson, 1981).

Bacteria, which have generation times in the order of hours, can reach a maximum population size in about one day (Kirchman and Mitchell, 1983). Significant bacterial film formation may occur within hours or it may take weeks, depending on environmental factors. In coastal waters, a rapid increase in film thickness occurs, with films more than 100 μm in thickness frequently observed within days (Mitchell and Benson, 1981). Terry and Edyvean (1984) reported a turf-like layer up to 4 cm deep of detrital material, bacteria, diatoms, other microalgae and associated mucilage on a platform in the North Sea.

Rates of bacterial colonization have been studied using panels coated with different antifouling paints (Dempsey[2], 1981). Initial colonization on control panels was rapid: bacteria were detected within four hours of immersion, reaching $2^5$ to $2^7$ cells/cm$^2$ after 8 hours and $2^{15}$ cells/cm$^2$ after 4 days. Numbers oscillated between $2^{15}$ and $2^{18}$ cells/cm$^2$ until the end of the experiment on day 23. These oscillations were probably due to the combined effects of succession, competition, and grazing within the bacterial populations.

Diatoms were apparent within 5 to 10 days on test panels immersed on the northeast coast of England (Edyvean and Terry[2], 1983). Depending on water temperature and season, dense blue-green algal and diatomaceous mats formed on these same panels within 100 days. Diatom density varied from 1,000 to 60,000 cells/$cm^2$ and reached a maximum density in 25 days. Densities were generally lowest during the winter months (January and February) and highest during spring and summer.

In other studies (Terry and Edyvean, 1984) mixed bacterial and diatomaceous slimes were reported with a thickness of 2 mm or more and containing 137,000 diatoms/$cm^2$. These same researchers recorded 270,000 diatoms/$cm^2$ in 28 days on newly immersed substrates in a similar study area.

The above description pertains to microfouling in coastal waters which have relatively high nutrient levels. It seems likely that the same series of events may occur in film development at oceanic sites (Corpe, 1979). However, rates of film formation and specific biological characteristics will probably differ with geographic location.

## 2.3 Settlement of Initial Macrofoulers

Larvae of many macrofouling organisms show preference for settling on surfaces coated with a multi-species microbial film. Several studies (Kirchman and Mitchell, 1981; Thomas and Allsopp, 1983; Neumann, 1979; Muller, 1973; de Silva, 1962; Carson and Allsopp, 1983; Dempsey[2], 1981) have demonstrated that larvae of benthic invertebrates and macroalgae prefer a substrate colonized by bacteria and other micro-organisms as opposed to a sterile surface. The mechanism by which the preferred substrate is "recognized" is not well understood. A number of different theories have been proposed including substrate texture, surface tension, and biological production of chemical cues from algae and invertebrates (Schelterma, 1974; Crisp, 1974; Mores et al, 1979).

Bacteria appear to be the group of micro-organisms in the films responsible for inducing settlement and metamorphosis of macrofoulers (Thomas and Allsopp, 1983; Kirchman and Mitchell, 1983). While some invertebrate larvae settle specifically on macroalgae (de Silva, 1962), the bacterial population on the algal surface cannot be ignored. The macroalgae may select for a specific bacterial population or induce polymer production by the bacterial film. However, not all bacterial species are effective inducers of either larval invertebrate settlement (Kirchman and Mitchell, 1981) or macroalgal settlement and/or growth (Thomas and Allsopp, 1983).

### 2.3.1 Lectin Model

Kirchman and Mitchell (1981, 1983) have suggested that "lectins" (proteins or glycoproteins) on invertebrate larvae bind specifically to carbohydrates (glucose polymers) found on the surface of the microbial layer. These carbohydrates may be produced by bacteria, algae, or invertebrates, although specific bacterial populations appear to produce extracellular glucose polymers which may induce settlement (Kirchman and Mitchell, 1981, 1983; Sutherland, 1980; Williams et al, 1979; Kirchman et al, 1981). In fact, glucose is a common constituent of extracellular polymers from many marine bacterial species (Kirchman and Mitchell, 1983).

Lectins are common in marine fouling organisms, and those invertebrate larvae which settle in a wide variety of surfaces may produce several lectins which recognize different polysaccharides or, alternatively, a single lectin which binds with low affinity to a wide range of polymers. It is suggested that binding of carbohydrates to the lectin on the larval invertebrate may initiate enzymatic activity inside the larvae, resulting in metamorphosis (Kirchman and Mitchell, 1983).

Work on the lectin model has not disproved other theories put forth to describe the early development of the macrofouling community. Physical factors undoubtedly influence polymer production and surface coverage by the microbial film. Other chemical cues such as cyclic AMP may be necessary to complete the induction of larval morphogenesis (Kirchman and Mitchell, 1983).

### 2.3.2 Mechanisms of Settlement by Macrofoulers

Biofouling is an inevitable phenomenon of the offshore environment. Fouling organisms are of a ubiquitous and abundant nature. A platform becomes colonized by the larvae and spore bearing currents that sweep past its isolated resting place. These larval stages of many fouling organisms have adaptive traits allowing them to withstand strong currents and survive for up to five weeks before settlement.

Macrofoulants arrive at the site of offshore structures by various means. Spores and larvae of intertidal organisms may be carried by water currents: e.g. Blue mussel, Mytilus edulis, kelp (Hardy, 1981; Houghton, 1978). Another area of invasion is from the sea bottom, from where organisms migrate to the offshore platforms (Houghton, 1978). Service ships and other vessels visiting the structures also contribute to the fouling community (Houghton, 1978, Evans, 1981, Moss et al, 1981). The importance of this means of transport is debatable except in the case of semi-submersibles where exposure to ships is of a longer duration. The most likely form of dispersal for Laminaria sp., a kelp found on North Sea platforms and along Atlantic Canada's coasts, is the young sporophyte. Moss et al (1981) suggests that the immature plants adhering in great numbers to the hulls of supply ships are of limited importance as a source of colonization. However, only a small number of first generation kelp spores need reach platforms, resulting initially in very sparse growth. These few individuals quickly grow into dense colonies (Oldfield, 1980). Some offshore platforms may be moored in coastal waters for varying times during final construction stages and before transportation to offshore destinations. This is especially true in the case of concrete structures. This presents a prime situation for the settlement of an initial fouling community (Houghton, 1978; Moss et al, 1981). Steel structures would not be exposed to this situation as the majority are launched from barges, first hitting the water at their final site (Picken, 1985, Personal Communication).

## 2.4 Succession and Settlement of Secondary Macrofoulers

Successional patterns are apparent within the macrofouling community, allowing for some degree of predictability. The primary settlers of a fouling community are barnacles and hydroids. Structural aspects of these organisms apparently induce settlement of other fouling organisms such as mussels and tunicates (Dean, 1981). Growth rates, temporal and seasonal abundance of larvae, and predatory activities are some of the mechanisms which result in successional patterns (Menge, 1976; Chalmers, 1982). Established hard fouling communities (barnacle and hydroids) may be completely replaced by soft foulers (tunicates) due to the smothering effect of the soft foulers on the hard foulers. Dense growth and the wave action of seaweeds and kelp may also disrupt established communities.

# 3.0 DESCRIPTION OF THE DIFFERENT TYPES OF FOULING ORGANISMS AND THE COMMUNITIES THEY FORM

## 3.1 Microfouling

Marine fouling is a serious economic problem on offshore structures caused by the rapid build-up of marine organisms and extracellular compounds produced by these organisms. The visible macrofoulers such as barnacles and macroalgae are preceded by a microbial community consisting of bacteria, fungi, unicellular algae (particularly diatoms), filamentous blue-greens, protozoa, and macroalgal spores (Table 2) (Terry and Edyvean, 1981; Mitchell and Benson, 1981). The microbial film produced by bacteria stimulates the subsequent settlement and metamorphosis of marine invertebrate larvae (Kirchman and Mitchell, 1983). Microbial films also induce and affect corrosion of metal structures, although this interaction is poorly understood.

Interactions between the microbial (microfouling) and macrofouling communities can be very complex. Further research on these processes should yield new anti-foulants that are more specific and more cost-effective than conventional anti-foulants (Kirchman and Mitchell, 1981).

TABLE 2

CONSTITUENTS OF MICROBIAL FOULING COMMUNITIES

A. Slime-forming organisms
   - bacteria
   - diatoms
   - protozoa
   - microalgae

B. Preliminary fouling organisms
   - hydroids
   - epiphytic algae

C. Primary fouling organisms
   - polyzoa
   - serpulids
   - barnacles

D. Secondary fouling organisms
   - mussels
   - ascidians
   - sponges
   - anemones

E. Adventitious organisms
   - polychaetes
   - nudibranchs
   - amphipods
   - other small crustaceans

As a fouling community develops additional rods, cocci, stalked forms, and prothecate bacteria can be detected. This resulting three-dimensional community will trap particles suspended in the water column. Algal spores and invertebrate larvae may become trapped, leading to the development of macrofouling. Nutrients released during bacterial mineralization of trapped detritus will act as either a direct or an indirect food source for all members of the fouling community (Dempsey[1], 1981).

### 3.1.1 Bacteria

Prominent bacterial genera found on newly colonized surfaces from several studies are listed in Table 3. Table 4 lists the percentage composition of bacteria from a study in North Wales (Carson and Allsopp, 1983). The predominant type of isolate was the Gram-negative rod of which 59 percent belonged to the family Pseudomonadaceae. Several reports of microbial film composition have also found the principal genus to be Pseudomonas.

### 3.1.2 Diatoms

Microalgal species generally employ different strategies of spatial utilization during community development. Settlement occurs with diatom cells initially grouped in separate monospecific clumps (Hudon and Bourget, 1981). Species diversity and abundance is low, gradually increasing with time. Eventually, with cell division, these diatom clumps begin to overlap and species diversity and cell density peak. This phase may be associated with the production of mucilage by specific diatom species (Blunn and Evans, 1981).

At first, the community is two-dimensional and appears as an amorphous horizontal mat of (Cocconeis spp. and Amphora spp.) and detritus. These diatoms are usually positioned with the raphe facing the substrate and have a tendency to occupy ridged areas (Hudon and Bourget, 1981; Terry and Edyvean, 1981).

TABLE 3

BACTERIAL GENERA ISOLATED FROM MICROBIAL FILMS

| | |
|---|---|
| Achromobacter | Hyphobacterium |
| Arthrobacter | Micrococcus |
| Bacillus | Pseudomonas |
| Caulobacter | Sarcina |
| Corynebacterium | Spirillum |
| Flavobacterium | Vibrio |

TABLE 4

PERCENTAGE BACTERIAL COMPOSITION OF MICROBIAL FILMS

| Genus | Percentage | Genus | Percentage |
|---|---|---|---|
| Alteromonas | 25.8 | Micrococcus | 5.4 |
| Pseudomonads | 19.4 | Flavobacterium | 4.3 |
| Coryneforms | 18.3 | Vibrio | 3.2 |
| Pseudomonas | 10.8 | Beneckea | 1.1 |
| Moraxella-like | 5.4 | unidentified | 6.3 |

With increased growth, some species (Achnanthes pseudogroelandica and Gomphonema kamtschaticum) orient themselves vertically (with the aid of gelatinous stalks, pads, or tubes) producing a three-dimensional community (Thomas and Allsopp, 1983; Patrick, 1977; Hudon and Bourget, 1981). Although the occurrence of stalked forms is apparently not dependent on the presence of horizontal species, the sequence of dominance always proceeds towards vertical colonizers. Some species (Synedra tabulata) form erect fan-shaped colonies, also utilizing the vertical dimension (Hudon and Bourget, 1981). Dominance by one species, usually a vertical colonizer, is often observed in a mature microalgal community.

TABLE 5

DIATOM GENERA ASSOCIATED WITH MICROBIAL FILMS

| | |
|---|---|
| Achnanthes pseudogroenlandica | Gomphonema kamtschaticum |
| Amphora costata | Gyrosigma articum |
| Amphora pusio | Navicula spp. |
| Biddulphia aurita | Navicula crucicula |
| Cocconeis costata | Rhoicosphenia curvata |
| Cocconeis scutellum | Synedra investiens |
| Coscinodiscus spp. | Synedra tabulata |
| Diploneis spp. | |

### 3.1.3 Blue Green Algae

Filamentous blue-green algae (Oscillatoria sp.) and colonial diatoms (Navicula spp.) are common to microfilms on the north-east coast of England (Edyvean and Terry[2], 1983). Other microfilms examined in this same area registered a thickness of several millimeters and were dominated by the diatom Achnanthes subsessilis (Blunn and Evans, 1981).

## 3.2 Macrofoulers

### 3.2.1 Hard and Soft Fouling Organisms

The macroorganisms of the fouling community are divided, for engineering purposes, into soft and hard groups:

1) Hard fouling organisms includes animals that are calcareous in nature, attach firmly to the surface, and have a specific gravity greater than that of seawater. For example, the specific gravity of mussel is equal to 1.3 to 1.4. This group includes barnacles, limpets, tubeworms, mussels, and calcareous (predominantly red) algae.

2) Soft fouling organisms have a specific gravity approximately equal to that of seawater and include anemones, sponges, sea squirts, kelp, and other algal species, hydroids, bryozoa, and rock borers (Stephens, 1977; Ralph et al, 1981; Anon.[1], 1980; Oldfield, 1980; Ralph and Troake, 1980; Gaythwaite, 1981).

These terms are quite arbitrary since some animal groups (e.g. hydroids and bryozoans) may contain both hard and soft species.

There are several hundred species of fouling organisms. North Sea platforms show in excess of 200 species (Forteath et al, 1984). Settlement and zonation of these organisms will vary according to environmental parameters; however, some degree of predictability is apparently evident.

### 3.2.2 Fouling Communities and Patterns of Zonation

The typical North Sea fouling community is dominated by a bivalve mollusc in the upper zone, with a barnacle and hydroid layer lower down. Seaweeds play significant roles in more mature communities. The species composition of a fouling community cannot yet be predicted with confidence solely on the basis of geographical location of the platform. Neighbouring platforms may contain significantly different colonies of organisms.

Ralph (1979) described the patterns of zonation in the southern North Sea as a mussel and soft hydroid dominant community from the surface to 30 m. Seaweeds were not considered significant foulers. Deeper levels showed a greater complexity of growth, with an initial hard fouling community composed of barnacles and oysters which was replaced within 3 to 4 years by soft foulers such as sea anemones and hydroids.

The vertical distribution of the major species on a typical platform in the north, south, and central North Sea was described by Pipe (1981). Typical fouling communities in the northern waters consisted of a greater diversity of organisms with mussels, algae, barnacles, and hydroids present in the surface zones (0 to -20 m). Central oil field fouling communities were predicted to be devoid of mussels, but dominated by algae at the surface. Fouling communities of the southern platforms were predicted to be mussel dominated.

Forteath et al (1984) concluded that a typical fouling community for a northern or a central North Sea platform did not exist. Some platforms in the northern North Sea showed mussel growth as dense as on centrally located platforms. Differences noted between platforms, for example the Forties and Montrose platforms, can only be explained by knowing the biological, chemical, and physical parameters of the sea to which the platform is exposed at the time of installation and throughout the years of service.

Wolfson et al (1979) discussed the function of offshore structures as artificial reefs off Huntington Beach, California. Numerous other papers have since been written that deal with the biofouling community of marine structures around the world in which patterns show some general consistency. For example, a local bivalve mollusc species is usually found as the dominant fouling organism on structures. The species Mytilus californius is found on the EVA platform in California, the green mussel Perna viridis is common on the Maui platform off the coast of New Zealand (Ralph and Troake; 1980). Mytilus edulis is dominant on the Hondo Platform in the Santa Barbara Channel (Sharma, 1983) and on the platforms of the North Sea. An area reportedly

lacking in a dominant mussel colony is offshore Louisiana. Apparently, this is due to the absence of prevailing currents in which mussel larvae could travel from coastal areas to offshore structures. Also, it is noted that the waters of offshore Louisiana are not nutrient rich, therefore limiting the diversity and extent of growth of any fouling communities (Heideman and George, 1981). Enteromorpha sp. is the most widely reported alga throughout the world. Some species of this genus are found on vessels and seawater structures in most waters (Fletcher, 1981). Enteromorpha is capable of withstanding wide fluctuations in temperature and salinity, and has a rapid mechanism for spore attachment (Evan, 1981), thus making it a successful fouling species.

Biofouling predictions have been made based on comparative studies of northern, central, and southern North Sea fields. The report of the Marine Fouling Working Party (1980) concluded that the northerly platforms of the North Sea would most likely consist of kelp-dominated fouling communities, differing from the mussel domination previously encountered on southern North Sea platforms. Oldfield (1980) described the sparse growth of hydroids, barnacles, and other fouling organisms on structures in the northern gas fields (Beryl and Frigg). Centrally located platforms (e.g., Forties, Auk, and Montrose) in the North Sea showed variations in density and dominance of species, probably due to the position of these platforms at the meeting points of currents. Southern gas fields contained climax fouling communities predominated by mussel growth. This area experienced extremely rapid colonization. Ralph and Troake (1980) discuss the variability of fouling communities on northerly and central platforms based on their position with respect to currents and coastal waters, the amount of space available, and the length of time they have been in place. The Forties and Montrose platforms are in relatively close proximity (40 km), yet their fouling communities greatly differ. The more northerly Forties platform is in the path of a well-defined current originating from the mussel-rich coasts of Scotland. The Montrose field is in the central area of the north sea and is not exposed to these larval-bearing currents. Mussel growth would predictably

dominate the Forties platform community and be extremely sparse on the more centrally located Montrose field, as was found to be evident in the existing situation.

Forteath et al (1982) suggest that the Montrose field is affected by the same larval-bearing currents as the Forties field. However, a greater length of time is needed for larvae to reach the central platforms of Montrose fields. This period of time needed for the current to reach the Montrose fields may exceed the lifespan of the planktonic mussel larvae, resulting in limited mussel growth on these platforms. The marine growth communities of the Beatrice platforms in the Moray Firth, North Sea were compared to the previously mentioned platforms by Forteath et al (1983). The Beatrice platforms located near the Scottish mainland are exposed to an abundance of larvae. Mussel growth was predictably limited due to the interspecific competition for space.

# 4.0 FACTORS CONTROLLING THE DEVELOPMENT OF FOULING COMMUNITIES OFFSHORE

## 4.1 Microfoulers

Geographical location is a major determinant of microbial film composition. Generally, diatoms are the predominate component of microbial films in Australian, New Zealand, and Indian waters, while bacteria predominate in North American, Adriatic, and Hawaiian waters (Carson and Allsopp, 1983).

Fouling is seasonal, and in temperate waters of the Northern Hemisphere, extends from the beginning of April to the end of October (Houghton, 1978). Environmental factors have a considerable influence on biofouling communities, controlling the fouling rate and species dominance in both microfouling and macrofouling processes (Mitchell and Benson, 1981). It is not yet possible to forecast with accuracy the possible influence of fouling on a structure without integrating a considerable amount of basic environmental information.

The kinetics of microfouling are closely related to seawater chemistry. Nutrient-rich waters rapidly yield thick biofilms, whereas nutrient-deficient waters either yield thin biofilms or the rate of initial film formation is slow (Corpe, 1979). Ultimately, however, biofilm formation is independent of the nutrient status of the water as the extracellular polymers act to concentrate nutrients (Mitchell and Benson, 1981).

Temperature influences the species present at a location and is an important factor controlling both time of attachment and growth of microfouling organisms. Both the number of microbes attaching to a substrate and the rate of bacterial and microalgal growth are directly related to water temperature (Hudon and Bourget, 1981). This close relationship is observed in the temperature range between 4 and 30°C (Mitchell and Benson, 1981).

Studies have shown a dramatic decrease in the quantity of microfouling and macrofouling with depth (Corpe, 1979; Mitchell and Benson, 1981). Not surprisingly, the best depth for growth of epiphytic bacteria and diatoms is known to be above 5 m (Hudon and Bourget, 1981).

It is probable that water velocity is an important factor controlling the rate of microfouling. However, the relationship is complex and involves the adsorption of nutrients onto the substrate that control the growth of the biofilm (Mitchell and Benson, 1981). Other factors are involved, including the nature of the microbe attached to the surface, the nature of the nutrients adsorbing to the surface, and temperature. Since these factors are continuously changing, it is impossible to predict the effect of flow rate on biofilm growth.

Other physiochemical factors such as salinity, pH, duration of immersion, and light intensity may also influence the season and depth of settlement as well as the rate of growth and abundance of microfouling species. Reduced light availability (high turbidity) and increased immersion times discourage both bacterial and microalgal growth (Hudon and Bourget, 1981; Corpe, 1979).

There is considerable controversy in the literature about the effects of substrate materials on microfouling rates in seawater (Mitchell and Benson, 1981). Data presented by Zaida et al (1984) and Marszalek et al, (1979) demonstrate that the interaction of marine microbial cells with surfaces in the sea can be quite specific. Different surfaces select bacterial populations with different morphologies. The source of this selectivity may reside in the specificity of the adhesion-enhancing macromolecules produced by these cells and the surfaces in question. However, little difference was detected in microalgae populations settling on a variety of different substrates (Terry and Edyvean, 1984). It is probable that bacterial mucilage plays an important role in masking any substrate differences. Similarly, by the time macrofouling larvae reach a substrate, it is completely coated with mucilage, so that the nature of the substrate surface becomes irrelevant (Mitchell and Benson, 1981).

Investigations of various inert natural surfaces such as rock and sand grains have indicated preferential settlement and development of bacteria and diatoms in cracks, holes, grooves, or alongside raised imperfections in the substrate (Hudon and Bourget, 1981; Houghton, 1978). This so-called "rugophilic reaction" is probably an anti-predatory mechanism and has also been observed on metallic surfaces. However, metallic surface texture has little effect on either film morphology or rates of microfouling (Beck et al, 1981).

It is believed that the chemical composition and surface charge of the metallic surface determine the quantity and quality of the biofilm. Studies using different metallic surfaces have provided interesting comparisons.

The fouling of rough and smooth surfaces of stainless steel illustrated a progression with time involving bacteria (10 days) and protozoa (15 days). Aluminum surfaces corroded very rapidly and were covered by aggregates of bacteria and an occasional flagellate protozoan in 6 days, and eventually stalked algae and sessile protozoa (coated with bacteria). Copper surfaces induced bacteria to form extracellular films. Titanium surfaces fouled most rapidly, forming a diverse and unique microbial community (Gerchakov and Sallman, 1977; Beck et al, 1981; Zaida et al, 1981).

Hydrophilic surfaces, such as glass and steel, generally acquire a small range of genera marked by a predominance of pseudomonads. In comparison, hydrophobic surfaces, such as resins and paint, acquire a much greater diversity of genera. This reflects the general ease of bacterial attachment and preference for hydrophobic surfaces (Carson and Allsopp, 1983).

## 4.2 Macrofoulers

The species present within a fouling community, and the extent of growth is dependant upon numerous factors including: the depth and distance from shore, temperature (seasons), light penetration, exposure, salinity, water current and quality, food availability, presence of

other organisms and imposed environmental stresses (cleaning, protection systems, etc.) (Anon.[1], 1980). Vast numbers of possible interactions amongst these variables are possible, therefore accurate forecasting of the abundance and species composition present in a community cannot be done yet with precision (Oldfield, 1980). However, useful forecasting is possible for some specific areas (Picken, 1985, Personal Communication).

Depth

Temperature, light penetration (which may also be affected by turbidity of water), and amount of available food decrease with increasing depths. As a result, there is a sharp reduction, with increasing depth, in metabolic and growth rates of the majority of organisms. Hydrostatic pressure will greatly increase with depth which may also act as a retardant, though it is not known to play a very significant role.

Zonation of species is evident with increasing depth; for example, the mussel community which is dominant from 0 to 9 m on one North Sea platform is replaced by anemones, sponges, and barnacles from depths of 9 m to 18 m (Hardy, 1981; Anon.[2], 1980). A similar zonation was also evident off the coast of Nova Scotia on the platform Sedco 706, where the dominant organism in the upper waters was M. edulis, and the bivalve Hiatella artica was restricted to deeper waters (Drinnan, 1984).

Distance of Platform from Shore

Since the majority of biofouling organisms arrive at offshore sites by way of water currents, the distance of the platform from shore will have a definite effect on the characteristics of the initial fouling community. Competition, predators, and natural succession all contribute to the development of a mature community which, once established, undergoes few major changes.

Seasonal Changes

Seasonal variations in marine fouling are to be expected because of associated changes in day length and temperature, as well as the natural life cycles of the various organisms. Temperature fluctuations are especially significant, and a rough guide is doubled growth rate per 10°C rise (Oldfield, 1980). The sea temperature range off the coast of Newfoundland is -1 to + 16°C (DePalma, 1969; Srivastava, 1976). Therefore, one would expect an approximate tripling of fouling activity during the summer season.

Platform Position and Exposure

Exposure of a platform also plays an important role in the colonization and growth of marine fouling. Wave "slam" will detach weaker members of the fouling community, especially young and old individuals, as well as any dead organisms.

Larvae of the major fouling organisms survive in the swimming stage for up to 5 weeks (Houghton, 1978; Oldfield, 1980). This allows ample time for water currents to carry them to offshore structures located in the current path.

The proximity of a platform to others will eventually be a contributing factor in determining the organisms present within the fouling community. Larvae from established communities will travel from one platform to another, resulting in a more uniform distribution of the fouling organisms.

Food Availability

Food availability does not appear to be a limiting factor for the growth of biofoulers in the North Sea. The highest concentrations of suspended nutrient materials are found in the more productive estuarine and coastal waters. It is unlikely that this will be a limiting factor in Atlantic Canada, considering the proximity of the rich fishing grounds to the offshore oil producing areas.

Presence of Other Organisms

Certain species cannot coexist due to predation, competition for the same resources, or habitat perturbation by one organism preventing colonization by another. Enteromorpha sp., for example, possesses qualities which inhibit the settlement of barnacle larvae (Houghton, 1978). Through predation starfish will quickly reduce the density of mussel growth on a structure. On a platform off the coast of California, a distinct zone of anemones beneath the upper mussel zone effectively deters starfish from reaching the mussels, since the slippery nature of the anemones prevents the starfish from crossing them to reach their prey (Wolfson et al, 1979). The perpendicular orientation of Mytilus edulis on the Beatrice platforms off the Scottish coastline protects the mussels from being smothered by soft fouling colonial organisms (Forteath et al, 1983).

Imposed Environmental Stresses

The settlement and growth of biofouling organisms has been at least partially detered through the use of antifouling systems. All of these systems are, so far, short term and some deal with coatings which leach various toxic substances. There is increasing concern over the long term impact of these chemicals on the marine environment. Other methods include gas bubbles, ultrasonic vibrations, biological means (for example, introduction of predatory organisms) and electrolytic systems. Cathodic protection systems, using large numbers of sacrifical anodes, and impressed current systems retard or prevent corrosion, but Oldfield (1980) suggests that the latter system may actually induce settlement of some organisms. Ralph and Troake (1979) found inconsistent settlement patterns of organisms on sacrificial anodes. It is debatable whether settlement was induced by the non functioning anodes or whether the settlement causes the anodes to malfunction.

The fouling community is periodically disrupted by cleaning and inspection operations. Density of a fouling community may be increased in areas that have been cleaned. Spores and larvae may be released by destruction of mature cells or by stress-induced release during

cleaning activities (Oldfield, 1980). Surface areas which receive periodic scrubbing may have a fouling community differing from the mature climax communities of nondisturbed areas (Hardy, 1981).

With knowledge of all the above factors, an approximate model describing the types and extent of biofouling could be developed. Accuracy would be improved through field studies to examine annual, short term, and long term fluctuations of the community. Through these studies predictable climax communities would become apparent.

# 5.0 CONSEQUENCES OF FOULING ON OFFSHORE STRUCTURES

## 5.1 Consequences of Microfouling

### 5.1.1 Corrosion

Metals have a natural tendency to return to their natural ore state. The process by which this occurs is termed corrosion (LaQue, 1975). Corrosion results from an electrochemical process, in which electrons are removed or lost from an atom of a given metal (oxidation). These electrons combine with (reduction) an atom in the surrounding substance or adjacent area. This migration of electrons or electric current from an anodic area to a cathodic area will vary with surrounding conditions, including:

| | | |
|---|---|---|
| Seawater properties | - | salinity, pH, $O_2$ content, temperature, and pollutants |
| Bottom conditions | - | erosion potential of sand |
| Wind and wave action, water currents | | |
| Biofouling | - | the action and interaction of marine bacteria and macrofoulants (LaQue, 1975; Arup, 1979; Doyle, 1981; Gaythwaite, 1981; Steensland et al, 1983; Southwell et al, 1984). |

Biological corrosion is the deterioration of a metal by corrosion processes which occur directly or indirectly as a result of the activity of living organisms such as bacteria, algae, and barnacles. Their life processes can affect corrosion behaviour in the following ways:

1. by directly influencing anodic and cathodic reactions,
2. by influencing protective surface films,
3. by creating corrosive conditions,
4. by producing deposits.

These effects may occur singly or in combination, depending on the environment and the organism involved (Fontana and Green, 1978).

In general, both microalgae and bacteria have been implicated by many authors in microbiological corrosion. More than 50 corrosion-producing microorganisms have been isolated. The bulk of publications, however, concern the anaerobic sulfate-reducing bacteria (SRB); second, the aerobic, iron bacteria and last, the microalgae and fungi. Many unrecognized microorganisms probably are involved in corrosion processes as well (Sharpley, 1973; Weber, 1983).

Breakdown of steel pipes or containers by bacterial corrosion occurs as a result of local perforation rather than wholesale deterioration (Stranger-Johannsen, 1983). Thus, even if the rest of the structure seems normal, local corrosion may be enough to undermine the integrity of a pipeline or tank. Such incidents have been reported from oil production facilities and structures all over the world.

The proposed mechanism for corrosion film formation (Edyvean, 1984; Tatnall[2], 1981; Salvarezza and videla, 1980) is as follows:

1. Slime formers (Pseudomonas, Aerobacter, Flavobacterium, and/or Bacillus bacteria) are free floating in the system and attach to the surface and multiply.

2. As the slime deposit grows, it traps suspended solids from the water, including iron oxides and free-floating filamentous iron bacteria (Sphaerotilus spp.), which thrive in iron-rich deposits.

3. The slime formers and iron bacteria consume any oxygen that diffuses into the deposit, thus forming an exaggerated anaerobic condition underneath.

4. Sulfate-reducing bacteria (Desulfovibrio, Desulfotomaculum, Clostridium) find their way into the deposits and concentrate in the anaerobic zone at the metal surface.

5. The combination of the oxygen-free condition and the sulfide generated by the sulfate-reducing bacteria destroys the passivity of the surface leading to localized corrosion.

6. Microfouling has a significant role in consolidating corrosion products on steel and considerable mats of microalgae have been found on the surfaces of corrosion products (Edyvean, 1984).

Once the corrosion inducing layer is in place, there are several possible mechanisms by which the presence of the microorganisms can influence surface corrosion. These include the setting up of concentration cells (including differential aeration cells); the production of metabolites such as organic acids, which may increase pitting corrosion; and the direct intervention with the corrosion process such as the cathodic depolarization of iron and steel by sulfate-reducing bacteria (Edyvean and Terry[1], 1983; Salvarezza and Videla, 1980).

5.1.1.1 Anaerobic Organisms

Probably the most important (and troublesome for offshore engineers) bacteria which influence the corrosion behaviour of iron and steel are the sulfate-reducing types (SRB). Sulfate-reducers, as a group, tolerate temperatures from <5 to 100°C, a pH range of about 5 to 9.5 and a wide range of osmotic conditions and hydrostatic pressures (Stranger-Johannessen, 1983; Tatnall[2], 1981; Pope et al, 1984). Since sulfate-reducers develop in water and mixed water/oil environments, they can be active throughout the whole oil production system.

To cause appreciable corrosion, sulfate-reducers must have an anaerobic environment, a source of sulfates and organic nutrients and available ferrous irons (Southwell et al, 1984). These bacteria use the sulfate ion as an oxidizing agent for the assimilation of organic

matter; the resulting corrosion product being iron sulfide (Tatnall[2], 1981; Fontana and Greene, 1978). Most strains also contain the enzyme hydrogenase which further catalyzes the reduction of sulfates by hydrogen. They use high levels of iron in their cell structure and are therefore prevalent in iron-rich environments (Tatnall[2], 1981).

Sulfate-reducers survive but do not grow under aerobic conditions. Therefore, in order to survive in oxygen-rich environments they co-exist with oxygen scavengers that create the required anaerobic conditions. Simple crevices or inert deposits will not support the growth of these bacteria without the presence of these scavengers. Slime-forming bacteria such as Pseudomonas are typical aerobic oxygen scavengers that attract, harbour, and shield sulfate-reducers from the bulk environment (Tatnall[2], 1981; Miller, 1980).

5.1.1.2 Aerobic Organisms

The volume of literature concerning the sulfate-reducing bacteria has tended to obscure the role of microorganisms in aerobic corrosion. Sulfur oxidizers such as Thiobaccillus (or Ferrobacillus ferrooxidans) oxidize sulfides to sulfates, thus producing sulfuric acid (concentrations 5 to 10 percent) (Fontana and Greene, 1978). They are strict aerobics, but often coexist with sulfate-reducers (Tatnall[2], 1981). To cause appreciable corrosion they must have a source of elemental sulfur. Other oxidizers (Thiothrix and Beggiatoa) are found primarily where there is an abundance of $H_2S$ and oxidize the sulfide to elemental sulfur. Although not usually directly blamed for corrosion, these bacteria form bulky slime masses well suited for harboring sulfate-reducers.

Filamentous iron bacteria (Sphaerotilus) oxidize dissolved ferrous iron to insoluble ferric hydrate. This forms a common sheath for several cells and produces a characteristic stalk-like filamentous form. Some varieties also oxidize and concentrate manganese. These bacteria are responsible for producing hollow hemispherical tubercles. They are aerobic and bring about oxygen depletion under the tubercles. This environment is corrosive in itself, but is made even more so when it harbours sulfate-reducers (Tatnall[2], 1981; Fontana and Greene, 1978).

Gallionella is another type of iron bacterium with uniquely corrosive tendencies. They tend to concentrate chlorides, such that their deposits are rich in highly corrosive ferric and manganic chlorides. This acts like dilute HCl and causes general corrosion of steel (Tatnall[2], 1981). Gallionella are aerobes, although they prefer limited oxygen. They often form dense mats, thus harbouring sulfate-reducers responsible for extensive pitting corrosion (Sharpley, 1973).

Mucilage produced by microalgal species (Oscillatoria and diatoms) and bacteria serves to concentrate sulfide compounds causing serious localized corrosion (Wilkinson, 1984; Terry and Edyvean, 1981). Microalgae can also dramatically modify local environmental conditions. Microalgal life processes can diurnally modify local pH values enhancing pitting corrosion (Terry and Edyvean, 1984; Edyvean and Terry[1], 1983).

Fungi in the Penicillium/Aspergillus group are also capable of effecting corrosion on metal surfaces (Siegel and Siegel, 1979; Pope et al, 1984; Sharpley, 1973). They produce a large number of organic acids which can initiate crevice attack corrosion (Fontana and Greene, 1978).

### 5.1.2 Mechanisms of Corrosion

#### 5.1.2.1 Anaerobic Mechanisms

There is much controversy concerning the mechanisms whereby sulfate-reducing bacteria induce corrosion on metallic surfaces. Several investigators believe that these bacteria directly cause (or accelerate) corrosion by removing hydrogen from cathodic sites or indirectly by iron sulfide absorbing hydrogen. Both processes result in cathodic depolarization (Edyvean and Terry[1], 1983; Pope et al, 1984; Sharpley, 1973) Some species (Desulfovibrio desulfuricans) also produce a highly corrosive metabolic end-product which is the major factor responsible for corrosion.

For corrosion to occur by this mechanism, the corrosive metabolite must have access to the bare metal surface (Iverson, 1984). A variety of other mechanisms for anaerobic corrosion by these bacteria include, 1) the production of corrosive metabolic by-products such as organic or inorganic acids (sulphuric acid), 2) the production of $H_2S$ and/or ammonia, 3) the prevention (by the microfilm) of corrosion inhibitors from reaching areas of active corrosion, 4) the absorption of nutrients (including oxygen) causing differential aeration cell and ion concentration cell formation (insoluble sulfides) (Tatnall[1], 1981; Pope et al, 1984; Gerchakov and Bernett, 1977; Miller, 1980; Iverson, 1984; Wilkinson, 1984).

5.1.2.2 Aerobic Mechanisms

The theories of aerobic microbial corrosion are mostly centered around the formation of concentration cells showing differential aeration (Sharpley, 1973). Many aerobic bacteria also produce potentially corrosive organic or inorganic acids under biofilms (Pope et al, 1984).

Cultures of blue-green algae have been found to enhance corrosion by anodic depolarization. This may be done by a method similar to that reported for aerobic bacteria, consisting of the breakdown of protective iron oxide films (Wilkinson, 1984; Terry and Edyvean, 1983; Edyvean and Terry[2], 1983). However, it is uncertain whether this corrosion enhancement is due to the algae themselves or associated bacteria.

5.1.3 Corrosion Rates and Results

Bacterial corrosion may proceed very rapidly and is dangerous because damage appears suddenly in very localized areas. The corrosion generated by bacteria generally takes a distinctive form (Tatnall, 1981). Sulfate-reducers produce open pitting or "gouging" as opposed to even corrosion (Stranger-Johannessen, 1983). The metal at the point of corrosion is characteristically graphitised and black iron sulfide is frequently found adhering to the corroded areas.

Under the hollow, hemispherical tubercles of iron bacteria will usually be found symmetrical hemispherical or conical pits. When slime formers are present, reddish brown deposits are generally more irregular and may show a layered appearance (Tatnall[1], 1981; Sharpley, 1973).

Several studies (Terry and Edyvean, 1981; Lewis, 1983; Sharpley, 1983; Tatnall[1], 1981; Engel, 1969; Hamilton and Sanders, 1984; Edyvean, 1984; Pope et al, 1984) have examined the susceptibility of different metals to microbial corrosion. Corrosion reactions at a metal surface are influenced by its surface characteristics and those of the electrolyte which in turn is influenced by the type of fouling organism present (Edyvean and Terry[1], 1983). Aluminum alloys were shown to corrode the fastest with pit depths up to 0.02 inches after a 6-month exposure. Surface corrosion of 2 to 3 mm was evident on magnesium alloys. However, only slight surface corrosion was detected on copper surfaces and no corrosive evidence was found on titanium surfaces.

Several studies have documented corrosion rates ranging from 1 to 4 mm/year in temperate and tropical oceanic regions respectively (Southwell et al, 1974; Lewis, 1982). Within a given area, corrosion rates can be highly variable depending on the substrate, local environmental conditions, and the microorganisms involved in the process.

### 5.1.4 Other Deleterious Effects

In comparison with the impact of microfouling-induced corrosion, other deleterious effects of these microorganisms (with respect to offshore structures) seem negligible. Certain microalgal species (Achnanthes subsessilis) produce a stalk which attaches the cell to the substrate. Other cells may be produced on top of the stalk-secreting cell, forming a colony. By raising the colony in this manner, the stalk increases the drag on moving structures (Blunn and Evans, 1981). The effect, however, would probably be insignificant in comparison to increased drag effects by macrofouling organisms.

Sulfate-reducing bacteria often produce poisonous hydrogen sulfide gas which by itself can be harmful to personnel working on oil rigs (Wilkinson, 1984). These bacteria also thrive with other bacteria generating hydrogen, methane, and assorted gases. Such gas releases can cause explosions (Stranger-Johannesen, 1983).

Furthermore, hydrogen sulfide sours oil and gas and microbial cell-masses can disturb processing by forming deposits and clogging filters, valves, pipes, or process control instruments (Stranger-Johannessen, 1983).

## 5.2 Consequences of Macrofouling

### 5.2.1 Weight and Hydrodynamic Loading

Offshore platforms are subject to wave and current induced forces. The magnitude of the forces depend upon the particular wave and current conditions: the size, orientation, and position of the structure with respect to mean water levels.

The "in-line" forces due to curents are proportional to the water velocity and to a drag coefficient, $C_D$.

Wave forces result from the orbital motion of water molecules. Any obstacle which does not move with these particles is acted upon by two force components:

1. Drag Component - due to the motion of water past the obstacle.

2. Inertia Component - partly due to the pressure differences which, in the absence of the obstacle, would produce the accelerative force for wave propagation and partly to the accelerative force involved in displacing the water that has to flow around the obstacle.

Structural engineers create design specifications for offshore platforms according to these fluid forces and the size, orientation, and position of the structure with respect to mean water levels.

The growth of marine organisms upon a structure will alter the criteria for design specifications. Marine fouling increases mass, surface roughness, and diameter of the structure. The increased mass and diameter due to fouling changes the physical characteristics of the structure with respect to mean water levels. Surface roughness will dramatically increase the drag coefficients which will have a major impact on current loading estimates. Wave loading is also increased by surface roughness; e.g., drag coefficient increases from 0.6 to 1.2 due to surface roughness, this induces a wave force increase by a factor of 1.6 (Anon[3], 1980).

The increase of wave and current loading forces as a result of marine growth can lead to the situation in which the design specifications of the structure are exceeded.

Heaf (1979) presented data on the effects of fouling in the North Sea and concluded that there were increases in both overall and local loading on a given platform. The consequences are more serious when the effect on fatigue life is considered, rather than on design wave loading. Marine fouling causes load increases as a result of (Oldfield, 1980):

- increased tube diameters: this means that there will be an increase in projected area and displaced volume, therefore hydrodynamic loading is increased,

- increased drag coefficients: which also increases the hydrodynamic loading,

- increased mass and hydrodynamic mass: leading to an increased dynamic amplification factor,

- increased structural weight.

Hard fouling organisms such as mussels and barnacles have a more serious impact on structural loading of platforms because of their greater weight and thickness (Eikers, 1978; Ralph and Troake, 1980;

Cammack, 1981; Ralph et al, 1981). Heideman and George (1981) suggested that the presence of soft, flexible foulers may actually lower drag coefficients by giving the offshore platform a more streamlined shape. Most researchers now think that the contributions of soft foulers to loading has been underestimated (Picken, 1985, Personal Communication). The presence of soft foulers results in a rough surface which increases the drag coefficient. Preliminary studies have indicated that loading forces as a result of soft fouling may be 40 percent larger than forces resulting from hard growth (Anon.[3], 1980). Suggestions indicate that the larger force generated by soft foulers is due to the fact that the inertial component, rather than the drag component, is affected by soft growth. More research is necessary to determine the relative hydrodynamic effects of different types of growth and to develop a standardization of soft growth dimensions to an equivalent hard growth thickness (Anon.[3], 1980).

Increased load due to fouling was not considered to be a problem on concrete structures because of their very large dimensions (Oldfield, 1980). The thinking on this is presently changing. Picken (1985, Personal Communication) states that excessive mussel growth is present at the surface zones which cause loading problems. Towers protruding from the platform act as long levers tending to rock back and forth on their bases. These problems are possibly further aggravated by scouring of sea bed around the platform base.

A biofouling layer of 50 mm can create a load increase of 5.5 percent (Gaythwaite, 1981; Hardy, 1981). Design specifications must, therefore, provide for a fouling allowance to prevent structural damage to offshore platforms. Southern North Sea platforms undergo periodic cleaning to prevent fouling thickness from exceeding design specifications (Picken, 1985, Personal Communication). Engineers must fully understand the implications on loading by fouling, not only in the design of the structure, but also throughout the structure's lifetime. As marine fouling changes in character, engineers must recalculate loading and fatigue.

### 5.2.2 Obscuring the Substrate

The presence of a macrofouling layer causes difficulties in inspection and general maintenance procedures.

Platform integrity or safety is dependent upon intermittent inspection or maintenance. Continuous inspection activities are also required to satisfy federal recertification programs (Cammack, 1981). Monitoring the extent of marine growth is a basic requirement.

Fouling presents a physical barrier which must be removed at significant cost to carry out appropriate inspection of underlying surfaces. Local surface cleaning is necessary to acquire cathodic protection, potential readings, wall thickness measurements (usually ultrasonic) and other corrosion checks. Risers and conductor clamps must also be cleaned for checking security. Other tasks are also necessitated by the interference of inspection programs by fouling organisms (Anon.[1], 1980).

Soft fouling colonial organisms greatly impede visual inspection by devices and remotely-controlled vehicles. Obelia longissima and Tubularia sp. form thick mats on large areas of platforms (Ralph, 1979; Ralph and Troake, 1980).

Gaythwaite (1981) suggested that abrasions and possible severance of mooring lines and cables could result from the close proximity to lines by hard fouling organisms. The operation of remotely-controlled systems such as "subsea completion units" may be hindered by the presence of Balanus hameri, a very large deepwater barnacle with a baseplate measuring 5 to 6 cm (Ralph and Troake, 1980). The valves of the seawater mains may become seriously blocked by mussels and barnacles if left untreated (Houghton, 1978).

### 5.2.3 Implications in Corrosion and Creation of Microenvironments

Corrosion in the offshore environment has the potential to become a key element in disasters, accidents, and often costly incidents, by

diminishing the integrity of offshore platforms (Paddock, 1981; Griffiths, 1982) Greatly increased maintenance costs result from frequently performed inspection programs necessitated by the threat of corrosion.

Offshore platforms can be considered as having three major external zones of corrosion: the atmospheric, the splash zone, and submerged portions. The degree of corrosion is highest in the splash zone where there is little opportunity for the metal to dry and atmospheric $O_2$ available to accelerate the process (Hedborg, 1974; Ross, 1978; Ellis, 1981; Anon.[1], 1980, Hasson and Crowe, 1982; Abrahami, 1983; Steensland et al, 1983).

The rate of corrosion of the structural metals within an offshore platform depends on: the corrosivity of seawater ($O_2$, pH, temperature); the physical environment (water velocity; erosion by particles, air bubbles, and ice); the engineering environment including the mechanical effects of fatigue and stress corrosion and the different metals used in a structure which can result in galvanic corrosion); exposure time; and the biological environment (fouling organisms) (Arup, 1979; Gaythwaite, 1981; LaQue, 1975).

The possibility that corrosion is accelerated due to the presence of macrofouling has been suggested by several workers (LaQue, 1975; Freeman, 1978, Ralph, 1979; Efird, 1981).

Living, decomposing, and dead fouling organisms release various chemicals, metabolic products, and/or adhesives which may also accelerate corrosion rates (Hardy, 1981; Gaythwaite, 1981).

There are many potential effects resulting from the presence of macrofoulants on a platform. Some may be beneficial, such as the insulation of the surface from the corrosive environment, or adverse, such as acceleration of corrosion rates (LaQue, 1975; Eikers, 1978; Anon.[1], 1980; Oldfield, 1980; Hardy, 1981; Ralph et al, 1979).

Macrofouling organisms can act as a sponge, retaining water on the surface of the structure. Water is retained beneath the frond of algal species (e.g. Entermorpha sp.) during low tide (Forteath et al, 1984), which increases the potential for a high corrosion rate within the splash zone. A dense fouling layer of various species will result in a moist layer constantly surrounding the platform.

Macrofoulers may indirectly contribute to the exposure of unprotected metallic surfaces to the corrosive environment. Cleaning the platform of fouling organisms, especially hard foulers will often result in damage to the protective coatings which have been applied to the metallic surface to reduce corrosion (Houghton, 1978). This is especially true in the case of removal of the byssal threads of mussels and the calcareous baseplates of barnacles. Detachment of the byssus is carried out by using abrasive wire brushes and force. This blisters and scratches the protective coatings, exposing the base substructure (Forteath et al, 1984). Once this steel has been exposed, conditions are favourable for bacterial growth and the concentration of metabolites (Edyvean, 1984; Wilkinson, 1984). Rhizoids of the seaweed Entermorpha sp. penetrate the coatings also resulting in blistering and cracking (Pipe, 1981; Forteath et al, 1984). The holdfasts of detached kelp, upon close examination, reveal pieces of the protective coating and metal clinging to the underside. The strong adhesive forces of the holdfast withstands the rigors of wave and current causing the bonding between the coating and the metallic surface to break (Forteath et al, 1984).

When the protective coatings are disrupted it is inevitable that any existing stable film will also be affected. The presence of a uniform film of corrosion products will reduce the rate of corrosion (Cleary, 1969; Luklinska and Castle, 1983). Macrofoulants cause the disruption of this film, revealing the base substructure underneath to the corrosive atmosphere through the methods described previously or through the behavioural patterns of colonizing foulers. The abrasive action of the sea urchin as it wanders about the platform surface removes the corrosion products, exposing the base metal surface to further deterioration (Gaythwaite 1981; Pipe 1981). Boring organisms

such as the mollusc Hiatella arctica may perhaps exert a similar effect (Pipe, 1981). Picken (1985, Personal Communication), however, states that no evidence of this exists and it's most unlikely. Barnacles grow in an outward and downward pattern. This results in the shaving of the protective coatings by the outer ridges of the barnacle. When the barnacle is detached by cleaning operations, the damaged coating is also removed (Pipe, 1981). Barnacles are also capable of "gouging" their way through 800 µm of coating annually (Forteath et al, 1984).

The presence of macrofouling organisms will also affect other imposed environmental conditions such as cathodic protection systems. The migration of electrical impulses may be hindered by the presence of a dense fouling layer (Oldfield, 1980; Ralph and Troake, 1980; Pipe, 1981; Steensland et al, 1983), thus inhibiting the proper functioning of the system.

Macrofoulers may create a condition which favours anaerobic corrosion. Many organisms act as filters and collectors, trapping large quantities of silt and detritus beneath their dense filamentous growth. This environment is ideal for the development of bacterial colonies which eventually deplete the local oxygen supply. It is within this oxygen-free environment that anaerobic bacteria proliferate, exposing the metallic surface to sulphate-reducing bacteria which are responsible for the ensuing corrosion activity regardless of marine fouling thickness (Southwell et al, 1974; LaQue, 1975; Eikers, 1978; Hardy, 1981; Pipe, 1981).

Another condition created by the presence of macrofoulers is that which favours concentration cell corrosion. This type of corrosion is caused by the formation of small pockets between the underside of organisms and the underlying steel. These pockets are characterized by irregularities in the ionic distribution and concentration of dissolved gases as a result of metabolic wastes, decomposition products, and de-oxygenated water. The presence of these conditions results in severe localized corrosion and pitting. Localized pitting present beneath the base of barnacles has been well documented (LaQue, 1975; Eiker, 1978; Ralph, 1979; Hardy, 1981; Gaythwaite, 1981; Pipe, 1981;

Steensland et al, 1983, Forteath et al, 1984). The decomposition of kelp holdfasts after cleaning operations also results in concentration cell corrosion. Sea squirts, soft corals, and hydroids often form dense colonies on top of barnacle beds, smothering the underlying barnacles. This results in a large area of decomposing material which contributes to corrosion by enabling reducing conditions to develop (Woolmington and Davenport, 1983; Forteath et al, 1984).

Woolmington and Davenport (1983) determined the pH and the $PO_2$ of the microenvironment beneath macrofoulers. The typical microenvironment beneath a fouling layer was found to have a pH level close to that of seawater and a decreased oxygen content. These characteristics, low oxygen level and an approximate pH value of 8.1, are not conducive to corrosion activity, thus a decreased corrosion rate may be experienced. Microenvironments beneath the sea anemone Metridium sp. were characterized by having extremely low pH values (as low as 5.0 in some cases) and high levels of oxygen intermittently available, due to their locomotive activity. High levels of oxygen and low pH values will greatly induce corrosive activity, increasing the corrosion rate of the underlying substratum.

Some macrofoulers are capable of producing highly corrosive products. Desmarestia viridis produces free sulphuric and malic acid when severely disturbed as a result of cleaning operations or rough seas, both of which are inevitable during the lifetime of an offshore structure (Houghton, 1978; Hardy, 1981).

Turbulence is created in the microenvironment beneath some organisms as a result of the locomotor activity or vibration of cilia. This leads to an increased water velocity and presence of air bubbles within a localized area favouring the acceleration of corrosion.

Macrofouling layers may benefit the integrity of an offshore platform by decreasing the rate of corrosion. Researchers have found that initially high corrosion rates of unprotected steel can be lowered by the development of a macrofouling community (Southwell et al, 1974). Dense marine growth can act as a barrier to the diffusion

of oxygen and will effectively insulate the underlying substratum from the abrasive action of strong water currents. Low oxygen values are not conducive to corrosion activity. The microenvironment beneath the fouling layer is partially or completely oxygen-free due to the respiratory activities of the organisms and the presence of aerobic bacteria, upon and within the fouling layer which utilize the incoming oxygen (LaQue, 1975; Eiker, 1978; Oldfield, 1980; Ralph et al, 1981; Hardy, 1981; Pipe, 1981; Gaythwaite, 1981; Forteath et al, 1984). Therefore, one would anticipate marked decreases in the corrosion rates. However, it is here that a paradox exists. The oxygen-free environment created beneath the macrofouling layer provides a suitable niche for anaerobic bacteria. This group of sulfate-reducing bacteria have qualities which induce corrosion of metallic surfaces. Establishment of the sulphate-reducing bacteria beneath the fouling layer results in a "equilibrium corrosion rate" (2.7 mm/yr) regardless of further increases in fouling thickness (Southwell et al, 1974). This steady-state corrosion rate is attributed to the production of sulfide films on the steel by the sulfate-reducing bacteria (Salvarezza and Videla, 1980; Hamilton and Sander, 1984).

Of the several hundred fouling organisms that are considered to be of major significance with respect to corrosion, the following were found to be the most common on North Sea platforms (Pipe, 1981):

| | | |
|---|---|---|
| i) | Algae: | Enteromorpha spp. |
| | (seaweeds) | Ulva spp. |
| | | Ectocarpus spp. |
| | | Desmarestia spp. |
| | | Porphyra spp. |
| ii) | Coelenterata: | Tubularia spp. |
| | (hydroids) | Sarsia spp. |
| | | Eudendrium spp. |
| | | Campanulariidae |
| | (anemones) | Metridium sp. |
| | (soft corals) | Alcyonium sp. |

| | | |
|---|---|---|
| iii) | Annelida: (calcareous tubeworms) | *Pomatoceros sp.*<br>*Hydroides sp.*<br>*Serpula sp.*<br>*Filograna sp.* |
| iv) | Arthropoda: (barnacles) | *Balanus spp.* |
| v) | Mollusca: | *Anomiidae*<br>*Mytilus edulis*<br>*Hiatella arctica* |

Each species may affect the rate of corrosion in several ways. For example, the sea anemone, *Metridium sp.*, induces concentration cell corrosion because of the low pH and high oxygen level in the microenvironment beneath it. The turbulence created by its locomotive actions accelerates corrosion by increasing the water velocity against the substrate. Sea anemones often colonize barnacle beds, eventually smothering the underlying organisms, resulting in large surface areas of decomposing materials. Anaerobic conditions arise underneath dense colonies of *Metridium sp.* allowing sulphate reducing bacteria to proliferate (Pipe, 1981; Woolmington and Davenport, 1983; Forteath *et al*, 1984). The seaweed, *Enteromorpha sp.*, penetrates the protective coatings and films through rhizoidal action, retains water in the splash and low tide zones, filters and traps suspended solids, and serves as a settlement site for other fouling organisms, increasing the density of the fouling layer.

The decrease in thickness of structural steel corrosion is estimated at 0.1 mm per year in calm water conditions. Areas and structures subject to marine fouling have an estimated corrosion rate of 1 mm/year (Cleary, 1969; Gaythwaite, 1981; Steensland *et al*, 1983).

Corrosion may be initiated as soon as the platform is immersed in marine waters. The ensuing formation of a fouling layer would obstruct detection of this initial corrosion. Following cleaning operations,

which may not take place for several years, this layer of corrosion would be noted and possibly assumed to result from the fouling layer. Therefore, although corrosion products have been found adhering to many of the fouling organisms on platforms, this does not necessarily imply that the corrosion results from the conditions prevailing beneath the fouling layer (Forteath et al, 1984).

These fouling organisms will almost certainly contribute to both adverse and beneficial effects on the platform integrity. Structural loading and impedance of inspection could, in the long term, cause problems, and certainly will be expensive generally throughout the life of the structure. As well, the fouling layer impedes the corrosion of the metal substratum by decreasing the available oxygen and insulating the surface from the corrosive action of the water current against the metal. The microenvironment beneath hydroids, tunicates, and limpets retards the corrosive process by restricting availability of oxygen.

The fouling layer may accelerate the corrosion rate by water retention, disruption of protective coatings, production of corrosion products, inhibiting the normal function of cathodic protection systems, and by creating conditions favouring anaerobic and concentration cell corrosion. The microenvironment beneath sea anemones has a low pH and intermittently high levels of oxygen. This favours an increased corrosion rate. Once a dense fouling layer has been established an equilibrium may develop in which the rate of corrosion resulting from the activity of anaerobic bacteria stabilizes, regardless of fouling thickness. This theory of equilibrium challenges the importance of imposed protection and antifouling systems.

# 6.0 SUMMARY OF METHODS FOR CONTROL/PREVENTION OF EXTERNAL FOULING OFFSHORE

## 6.1 Microfouling Control

### 6.1.1 Physical and Chemical Control

The fouling of submerged surfaces has been a problem since man first utilized the aquatic environment. Early attempts to prevent fouling and corrosion were empirical and simple, consisting of painting the structure with pitch or cladding with a layer of metal. Subsequently, antifouling compositions were developed which contained toxic copper, lead and tin compounds. These were applied in the form of paints based on linseed oil, which has now been largely replaced by synthetic polymers (Thomas and Allsopp, 1983).

Today, offshore structures are protected from corrosion by various methods. Above the waterline they are coated with paint formulations containing inhibitive coatings. The submerged zone is protected by impervious coatings and by cathodic protection. The latter is an electrochemical method of protection achieved either by an impressed current or by the use of sacrificial anodes. An alloy sheath is sometimes used in addition to paint coatings to protect the splash zone (Terry and Edyvean, 1981).

However, toxic coatings commonly used for control of macrofouling are, for various reasons, not effective against microfouling (Dempsey[2], 1981; Corpe, 1979). Most of the effort to date in the matter of microfouling control has involved attempts to scrape or brush the slime from the solid surface. Results show that microfouled surfaces can be relieved of some of the accumulated material, but the slimey film again becomes reestablished and in a much shorter time than was required for it to form in the first place (Mitchell and Benson, 1981). This technique merely knocks the top off the film, regenerating soluble nutrients and stimulating growth of the remaining microorganisms. Effective film removal by scraping alone will only occur by exposing new metal (Corpe, 1979; Beck et al, 1981).

Microfilm formation can also be discouraged by chlorinating the water, but this has led to the formation of unacceptable pollutants (Mitchell and Benson, 1981; Beck et al, 1981).

Ultrasonic cleaning has been suggested as a means of controlling microfouling, as high-intensity ultrasound has been used to destroy waterborne bacteria (Mitchell and Benson, 1981). However, preliminary testing did not completely remove bacterial slimes and only partial control of these slimes would not be acceptable.

Organotin (biocide) paint formulations have recently been improved and are highly successful in preventing fouling by macroalgae. Unfortunately, they are still unsuccesful in controlling diatom-dominated microfouling slime (Callow and Evans, 1981). It is believed that stalk formation by these diatoms moves the cell into a region of lower toxity, thus reducing the effectiveness of the biocide. In addition, 85 to 90 percent of all fouling bacteria are resistant to the toxic effects of organotin antifouling compounds (Dempsey, 1981[1] and [2]).

Control of microfouling may be possible if we are able to learn enough about the process to be able to effectively interrupt it. Development of a surface unsuitable for adsorption of conditioning agents and/or attachment by bacteria or manipulation of the initial wettability of the surface may be possible methods of slime control (Corpe, 1971; Gordon et al, 1981; Beck et al, 1981; Mitchell and Benson, 1981). The discovery of an inhibitor of either bacterial growth or mucilage production would also help to control microfouling processes and biofilm development (Dempsey[1], 1981).

### 6.1.2 Biochemical Control

The biochemical study of lectins on invertebrate larvae could provide a powerful new insight into the mechanisms of settlement and metamorphosis. This information would be invaluable to the development of innovative fouling controls. It may be possible to block the lectin-polysaccharide bond with artificial lectins (low molecular

weight sugars) that compete against the larval lectin for receptor sites on the microbial surface (Kirchman and Mitchell, 1983). Artificial lectins could be developed that control specific foulers endemic to a region. Specific anti-foulants would be more effective and less costly than anti-foulants that are toxic to a broad spectrum of organisms. Alternatively, it may be possible to disrupt the lectin-polysaccharide bond at a biochemical level which would inhibit all fouling organisms (Kirchman and Mitchell, 1981).

## 6.2 Macrofouling Control

Macrofouling becomes established only after the formation of a microfouling layer. Therefore an effective means of controlling microfouling will presumably inhibit the formation of a macrofouling layer. The extent of this inhibiting effect depends on the control method being used.

Macrofouling has a greater ability to impede inspection and contribute to loading forces than microfouling due to its size. These adverse effects of macrofouling may be intermittently reduced through various control methods that are not practical for microfouling control.

### 6.2.1 Cathodic Protection Systems

Cathodic protection systems are effective against corrosion which may be induced by the microfouling and macrofouling organisms. The anodes of the sacrificial anode CP system may also influence growth patterns of macrofoulants (Ralph et al, 1981). There are a number of ways in which the anode is colonized by marine growth, some are completely free of growth, while others are covered in a dense layer. It is not known whether functioning or nonfunctioning anodes trigger the colonizing response.

### 6.2.2 Antifouling Paints and Biocides

Macrofouling organisms may be deterred through the use of biocides or antifouling paints. Specific types and quantities of these substances

are required to prevent fouling, depending on whether macro- or microfouling are present and the particular fouling species. For example, copper-based antifoulants are effective inhibitors to ship fouling. A leaching rate of 10 µg $Cu^{++}$ $cm^{-2}$ $day^{-1}$ prevents settlement of most macrofouling organisms (Barnacle larvae). Sensitive macrofoulers, such as mussels, are deterred by leaching rates of 1 to 2 µg $Cu^{++}$ $cm^{-2}$ $day^{-1}$. Accumulation of diatoms and bacterial slime can only be prevented through the use of leaching rates in excess of 20 $\mu g/cm^2$ day (Evans, 1981). This is not economically feasible. The use of anti-foulants and biocides to control offshore fouling is of a predictably limited scope due to their restricted period of active toxicity. The use of thick coats of these substances have proven to be somewhat effective when used in combination with cathodic protection systems (Houghton, 1978).

### 6.2.3 Mechanical Removal of Marine Growth

Mechanically removing the fouling is an effective means of temporarily diminishing a loading problem caused by macrofoulers or to allow inspection of specific sites on the platform.

Various devices may be used to mechanically remove marine growth (Anon.[1], 1980):

1. Water Jets - This method is suitable for rough cleaning only. The surface of the structure is not bared for close inspection with this method. Remotely controlled vehicles may transport these devices at extreme depths. Water jets are extremely successful in terms of rapid removal of soft growth. Some problems associated with this method are high levels of noise and turbidity which greatly reduce divers' communication, visibility, and effective results are only achieved through the use of skilled operators (Anon.[1], 1980).

2. High Pressure Water Jets - This method works on the same principle as the previous method but with high levels of pressure (105 $MN/m^2$). High pressure water jets are capable of cleaning surfaces to the

inspection standard. Some problems associated with this method: the actual effect that this much pressure has on a steel surface is not known; small cracks or defects in the surface may be masked or altered by the force of the jets (Anon.[1], 1980).

3. Abrasives - Abrasives are used in combination with water jets diminishing the amount of pressure needed to achieve the same results. A water/abrasive jet with 27 $MN/m^2$ pressure is as effective as a 70 $MN/m^2$ plain water jet (measurements taken on land). Some problems associated with this method: large amounts of damage may result on steel surface, more so that with water jets; transportation of abrasives to the site is difficult; reduced diver visibility due to turbidity, and this method has a maximum operating depth of 60 m (Anon.[1], 1980).

### 6.2.4 Other Methods

#### 6.2.4.1 Thermal Shock

Exposure of marine growth to hot water or steam treatment is another method of temporarily controlling fouling problems. After this treatment, organisms are weakened or killed, allowing subsequent wave action to remove the debris. A major obstacle to implementing this method is how to supply adequate amounts of hot water or steam to the surface. New procedures of application are needed to prevent rapid dilution and cooling (Anon.[1], 1980).

#### 6.2.4.2 Biological Means

Biological means of control include the encouragement of predators or seeding the platform with more desirable growth. An example of biological control through the use of predators was implemented on a platform off Santa Barbara (Anon.[1], 1980). Mussels were causing severe loading problems on this platform. The seabed surrounding the platform was covered in starfish which were hindered from reaching their prey by a band of anemones. Pathways were cleared through the anemone zone by divers to allow the starfish to reach the mussels in the surface zones.

Woolmington and Davenport (1983) suggested that the microenvironments beneath some marine macrofouling organisms may induce more rapid corrosion rates than other macrofoulers. For example, the microenvironmental conditions beneath sea anemones (Metridium sp.) are more conducive to corrosion than the microenvironmental conditions beneath hydroids (Tubularia sp.). Introduction of hydroids to the platform surface would enable an environment less conducive to corrosion. Unfortunately, long term control of marine growth using this method is extremely unlikely as the fouling community eventually reverts to its natural succession.

#### 6.2.4.3 Biotechnology

Biotechnology utilizes the new technique of "genetic engineering." Genetic engineering allows the excision of genetic material from the producing organism and transfer into bacteria whereby the compounds, metabolites, or gene products can be produced by the bacteria in the laboratory (Colwell, 1984). Current studies in the U.S. are employing techniques of genetic engineering to develop antifouling agents by developing inhibitors that function at the molecular level. This method of control has great potential.

### 6.2.5 Requirements for the Future

The method used to control marine fouling should be an independent system which does not cause accelerated corrosion and prevents or removes fouling effectively. It must be cost-effective, easy to install and maintain (Houghton, 1978).

# 7.0 POTENTIAL FOR FOULING OF OFFSHORE STRUCTURES ON THE EASTERN SEABOARD OF CANADA

## 7.1 Pnysical Parameters of Atlantic Canada's Water

The Labrador Current flows down the east coast of Newfoundland with surface temperatures as low as -1.5°C in winter. The warmer and more saline layer originating within the offshore areas of the Labrador current is effectively trapped beneath this surface layer of cold water. With the arrival of spring's warmer temperatures, the surface water becomes lighter and may reach temperatures above 10°C. Beneath this layer is the dense, cold layer and the deeper warmer layer. In shallow areas the deeper, warmer water does not exist, resulting in very cold temperatures year round (<0°C). The salinity also shows large fluctuations due to the combination of the low saline Labrador waters and the warmer saline waters of the Gulf Stream. The mixing of these two results in a complex oceanographic situation. More so than in the North Pacific, the North Atlantic surface waters are super-saturated with oxygen. Below 500 m an area of minimum oxygen is present in the North Atlantic (5mL/L). The pH of the seawater varies with the $CO_2$ levels; exhibiting higher levels in the upper zones, decrease in the minimum oxygenated layer, and then an increase in deeper waters (Srivastava, 1976).

The area off the east coast of Canada is exposed to some of the strongest ocean currents in the world. The Gulf Stream may travel at speeds of 250 cm/sec (5 knots) (Srivastava, 1976).

The physical attributes of Atlantic Canada waters will have an impact on the fouling community of this area. Brisk ocean currents may hinder larval settlement of some seaweeds. Abrupt temperature changes within the water column may alter the zonation patterns of the fouling community.

## 7.2 Summary of Existing Fouling Data From the Atlantic Region

Mussels, kelp, and Entermorpha sp. are certain to be of importance as members of biofouling communities occurring on structures in the east coast waters of Canada, considering their importance in the fouling community of previously encountered platforms and their abundance on nearby coasts. Many major foulers of the North Sea area are also present in Atlantic Canada's waters. Soft fouling (sea anemones, sponges, bryozoa, and hydroids) and hard fouling organisms (limpets, tubeworms, barnacles) are prolific in eastern Canadian waters. Broad conclusions for the colonization and zonation of these organisms may be made based on data collected from previously encountered platforms in the North Sea, and from data collected on the fouling communities found on a variety of immersed substrates.

The basic fouling organisms of Penobscot Bay, Maine, and Placentia Sound, Newfoundland, were determined by DePalma (1969) using test panels. The fouling communities were termed Boreal, consisting of cold water organisms. The upper areas of the water column showed heavy mussel and kelp growth. Below this, barnacles and other hard foulers predominated. It was noted that 4-year old panels did not differ in species content from those left in the water for shorter periods of time. Studies in the North Sea suggested a much longer time was required to establish a climax biofouling community.

In a more recent study of the SEDCO 706 Grand Banks offshore platform by Drinnan (1984) the approximate weight of biofouling was determined, while the platform was out of water for repairs. This study revealed four distinct zones of growth with a predominant mussel (Mytilus edulis) layer in the surface zone (100 percent mussel weight). The dominant species for the lower zones were the small clam (Hiatella artica) and barnacles (Balanus sp.). The author estimated that the biofouling contributed a net weight (in water) of approximately 23,000 lbs. to the platform. However, the sampling was performed after the rig had been in harbour for an unspecified period of time, during which the fouling community, exposed to the air, had perished. No information is provided on the thickness of the biofouling, nor on the

ratio of the net weight of biofouling to the size of the Sedco 706. A more thorough study of benthic invertebrates was completed by Davis (1976), in which the species of pelagic organisms and their distribution were determined in the Sable Island area off Nova Scotia.

In the Lower St. Lawrence Estuary diatom diversity in microfilms peaked in September at 20 species, many of which are listed in Table 5 (Hudon and Bourget, 1981). Cocconeis spp. and Amphora spp. were major diatom colonizers from May until mid-August. In September, Synedra tabulata dominated microfilms.

In the St. Lawrence study, diatom colonization occurred 2 to 7 weeks after initial bacterial growth. During peak periods, the density of a single diatom species reached 1,485 cells/$mm^2$. Population density averaged 675 cells/$mm^2$ during the summer months.

Counts of 30 million bacteria/gram of mucilage have been reported in western Atlantic waters after only a few hours of substrate immersion (Terry and Edyvean, 1984). Fifteen to twenty days following immersion, bacterial counts on test panels stabilized between 20 x $10^4$ and 40 x $10^4$ cell/$mm^2$ in the St. Lawrence Estuary (Hudon and Bourget, 1981). The documented number of viable cells present in natural seawater is in the range $10^3$ to $10^4$ cells/mL (Thomas and Allsopp, 1983).

## 7.3 Identification of Potential Foulers

There are approximately 15 fouling organisms which are of major significance to corrosion in North Sea waters. The majority of these organisms are known foulers in the waters of Eastern Canada and thus may be of similar significance to corrosion problems in this location.

However, conclusive evidence linking macrofouling cover to ongoing observed corrosion has not been found, therefore the following list is somewhat subjective (Picken, 1985, Personal Communication).

A list of fouling organisms, thought to be of major significance to corrosion, commonly found in Atlantic Canada would share similarities in content to the list of North Sea fouling organisms. Other distinctly "Canadian" species will also be involved (DePalma, 1969; Davis, 1976; Drinnan, 1984).

Algae: Enteromorpha spp., Ulva spp., and Laminaria spp. dominate the plant fouling community. Sparse growth of Desmarestia sp. and Porphyra sp. was found in eastern Canadian waters.

Coelenterata: Obelia sp. covered in excess of 40 percent of panel surfaces immersed in eastern Canadian waters during a study of the fouling community. Tubularia sp. and Sertularia sp. were found in lesser numbers. Sparse Metridium sp. growth was noted.

Annelida: The calcareous tubeworm Spirorbis spp. is abundant throughout the Atlantic Canada region. Hydroides sp. and Filograna sp. are present to a lesser extent.

Arthropoda: Atlantic Canada, like the North Sea region, has a large population of barnacles (Balanus spp.) which are the only Arthropoda of major significance to the corrosion problem.

Mollusca: All three molluscs of major significance to corrosion on North Sea platforms are those found in greatest abundance in Canadian waters (Anomia spp. Mytilus edulis, and Hiatella arctica).

Many of these fouling organisms will also be of major significance in terms of hydrodynamic and weight loading. Notably Laminaria sp. and Mytilus edulis.

## 7.4 Predictions

Several studies have been undertaken to investigate the predictability of fouling in the North Sea. Houghton (1979) discussed the probabilities for several species of foulers. Dominant species were proposed on the basis of information from ship and seawater main fouling communities and suggestions were offered for the probable existence of zones of organisms characteristic of specific geographical sites (Houghton, 1978). Freeman (1978) indicated that the underwater fouling of offshore structures was much greater than previously forecast, and that there was an urgent need for biological fouling charts and growth data to help determine the predicted impact of fouling communities on offshore structures.

Recent studies in the North Sea by the Offshore Marine Studies Unit have provided accurate data and biofouling charts. This information enables more accurate future forecasting.

Atlantic Canada's offshore industry is still relatively young. Biofouling data has been accumulated from coastal and nearshore communities or from short term studies on offshore structures. This information is too general to allow accurate forecasting of the fouling community, however some very broad predictions may be made:

- Microfouling communities in western Atlantic waters would have a similar composition to those in eastern Atlantic or the North Sea due to the universality of the genera involved.

- The harsh environment and low temperature of Canada's east coast are best utilized by "Boreal" or cold water organisms.

- Mytilus edulis will predominate in the surface zones significantly affecting loading forces.

- Kelp is prolific throughout the east coast of Canada and will most certainly be an important macrofouler. The importance of kelp as a fouling organism is often underestimated due to the length of time involved in establishing a successful colony.

- The lower zone of east coast structures will predicably be settled by predominant barnacle growth. As the fouling community matures, soft bodied organisms (sea anemones, hydroids) may settle, smothering the underlying hard growth.

- These fouling organisms will be present in great quantities and have signficant impact on loading, impedance of inspection, and corrosion rates.

## 8.0 CONCLUSIONS

The consequences of biofouling include the initiation and acceleration of surface corrosion, increased loading and drag, and difficulties in general maintenance and inspection of offshore structures. Biofouling may have beneficial qualities which can aid in the longevity of a platform as well. The presence of a biofouling layer can result in a decrease of longterm corrosion rate due to its insulating properties. The oxygen-free environment between this insulating layer and the surface of the structure inhibits all but anaerobic bacteria, which can lead to a reduction and levelling-off of the rate of corrosion.

From the review of available information on biofouling and biocorrosion, particularly as it refers to Atlantic Canada's offshore petroleum industry, the following can be concluded:

i) Biofouling community characteristics (species composition, density, diversity, succession, and phenology) appear to be site specific. The factors contributing to this specificity include: geographical locations, hydrographic characteristics (current velocity and direction, temperature, salinity, turbidity, and water chemistry), season, latitude, source of inoculum, distance from shore, proximity to other structures, local marine flora and fauna, and platform activities.

ii) The multiplicity and complexity of the factors which determine the nature of a fouling community prohibit making reliable predictions, except in the broadest terms, concerning the characteristics of fouling communities developing at new sites. Quantitative data that engineers will require for efficient design and safe operation and maintenance of offshore structures on the eastern seaboard are not available and cannot be reliably deduced. Therefore, a field programme is necessary to assess the problem.

iii) Biofouling, as an important factor in the safe and efficient operation of North Sea platforms, has been clearly recognized and considerable joint government industry efforts have been applied to fully recognize and determine the magnitude of the biofouling impact.

v) Significant advances have been made in understanding the role of microbial organisms in the biocorrosion processes. The nature of the microbial community depends upon the nature of the macrofouling community under which it develops. By inference then, detailed knowledge of the microfouling community depends to a strong degree on the extent of information available on the macrofouling community.

vi) By understanding the microfouling community and its relationships with its substrates, there appears to be an opportunity for using these newly elucidated relationships in the development of more effective protection systems.

## 9.0 RECOMMENDATIONS

Based on these conclusions, we recommend the following actions to be initiated by industry and government in approaching the industry-wide problem of biofouling and biocorrosion.

i) There is need for a program whose objective would be to develop the data base for assessing potential impacts of biofouling/ biocorrosion on offshore petroleum structures in Atlantic Canada. This program needs to ascertain:

   a) the vulnerability of structures in various locations to fouling,

   b) the rates at which fouling will occur,

   c) the anticipated coverage and thickness of the different types of fouling.

ii) An ongoing program should be established to further elucidate the processes of microbial biocorrosion, particularly in reference to the marine environment and impacts on offshore petroleum structures.

iii) A program needs to be developed in which the information gathered from research studies on macro- and microfouling community characteristics in the Atlantic can be utilized for predictive purposes.

iv) A program of industry-government participation needs to be put in place which will focus attention on the importance of biofouling and biocorrosion in the safe and successful exploitation of Atlantic Canada's offshore hydrocarbon resources.

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